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The adaptive x-ray optic project at the Lawrence Livermore National Laboratory

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Abstract. Deformable mirrors (DMs) have been successfully used in astronomical adaptive optics at near-infrared wavelengths, greatly reducing atmospheric-induced aberrations [1]. Extending this capability to the soft and hard x-ray regime is now required in order to take full advantage of the beam quality characteristic of new generation synchrotron facilities and X-ray Free Electron Lasers (XFELs). Achieving this goal challenges both current mirror manufacturing techniques and physical optics modeling. The Lawrence Livermore National Laboratory (LLNL) is currently developing an x-ray DM to correct wavefront aberrations introduced along the beam path of a typical x-ray beam-line [2]. To model the expected performance of such a mirror, we have also developed simulation code based on the wavefront propagation library of functions PROPER [3]. Here we present the current status of the project, including metrology done on the mirror substrate. Additionally we report on results from our wavefront simulation code, which have proven very useful in predicting technical aspects of mirror deployment at a typical x-ray facility.

1. Why Adaptive X-ray Optic?

XFELs and modern 3rd generation synchrotrons are challenging our ability to handle their spatially coherent x-ray beams. While diffraction limited at the source, the beam accumulates phase and amplitude errors by interacting with transport x-ray mirrors during its propagation to the end-stations. The result is a diminished beam profile uniformity. Polishing x-ray optics to Ångström roughness and nanometer figure errors is mandatory to mitigate this problem; however the cost of these optics is considerable and their often harsh environment can contribute to degradation of surface quality with time. The demand for highly uniform beam profile is common among FEL and synchrotron users; improved beam profile uniformity would increase resolution in imaging of biological samples; at the same time the capability of custom-shaping the beam profile would benefit experiments such as pump-and-probe (see fig 1). Adaptive X-ray Optic (AXO) promises to address these demands.

2. The Adaptive X-ray Optic Project at LLNL

LLNL is in the process of building a DM with the goal of quantifying its impact on wavefront propagation at a typical x-ray beamline. The AXO project is currently in its third year of funding. The project deliverables are (i) a 450mm long DM, (ii) a custom-built wavefront propagation code designed to predict mirror performance and optimize mirror integration with an x-ray beam line [2], and (iii) the development of a theory to analyze aliasing in wavefront
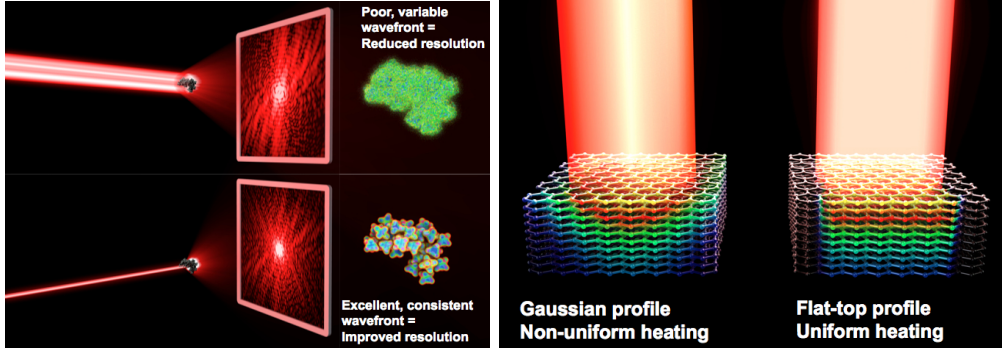
Figure 1. Artist rendering of AXO expected capabilities: (left panel) an aberration-corrected wavefront will enhanced resolution in x-ray imaging experiments on biological samples. (right panel) The beam-shaping capability of AXO will allow uniform sample heating in ultra-fast transition experiments in solids. Rendering by Kwei-Yu Chu (LLNL)
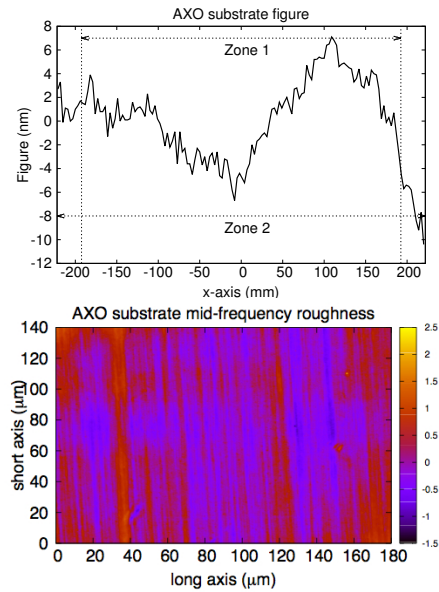
sensing at x-ray wavelengths [4]. The project is the combination of LLNL extensive expertise in x-ray optics and adaptive optics applied to astronomy.

2.1. The hardware

A 450mm-long single crystal silicon substrate has been super-polished to 3.5Å rms roughness and 3.5nm rms figure error. The substrate is 40mm thick and 30mm wide; its polished surface has been extensively characterized at LLNL via long aperture interferometry, white-light interferometry and atomic force microscopy. Fig 2 shows a selection of data collected at LLNL. Deformable surface technology is provided by AOA Xinetics (Northrop Grumman); 45 1-cm wide actuators are being installed on the back of the mirror, with one strain gauge per actuator. Calibrated strain gauges will be used at first to provide close loop operations even without a wavefront sensor. The fully actuated mirror is expected at LLNL by August 2013.

2.2. The software

Successful implementation of an x-ray DM strongly relies on the availability of a wavefront propagation code to predict mirror performance and help with deployment of the mirror at an x-ray facility. LLNL has develop a full physics optic propagation code based on the PROPER library of functions written for


Figure 2. Selection of metrology data acquired on the AXO substrate: (Top panel) Large aperture interferometry data across mirror full aperture; (bottom panel) White light interferometry data taken with 40x lens

IDL [3]. In this manuscript we present simulations ran using the beam transport system of the Linac Coherent Light Source (LCLS, SLAC) [5] as a test case. Photons with 8 keV energy and a gaussian beam with 60μm beam waist were used in all simulations. The goal of these

preliminary simulations is to quantify the kind of improvement that will be achieved once we deploy our DM at a state-of-the-art x-ray facility. Figure 3 shows the simulated unfocused beam profile at the far experimental hall (FEH) of the LCLS after reflection off the two mirrors in the hard x-ray section of the beam transport system [6]. The low intensity wings at both sides of the peak are caused by figure errors on the offset mirrors. The ideal, diffraction limited beam is also shown for comparison. The result agrees with the published work of Barty and coworkers [7].

In order to estimate wavefront correctibility provided by our DM, we ran additional simulations replacing the two LCLS hard x-ray off-set mirrors with two adaptive mirrors; these adaptive mirrors have the same specifications as the one under development at LLNL, including figure errors consistent with the results of our metrology on the mirror substrate. Code output confirmed that a considerable improvement in beam profile uniformity would be achieved within the actuation range of the mirrors. The result of this simulation is shown in Fig 4.
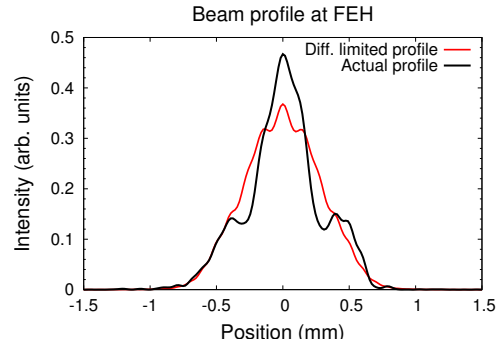

Figure 3. Beam profile at the Far Experimental Hall of the Linac Coherent Light Source (solid line). The diffraction limited psf is also shown with a dash line.
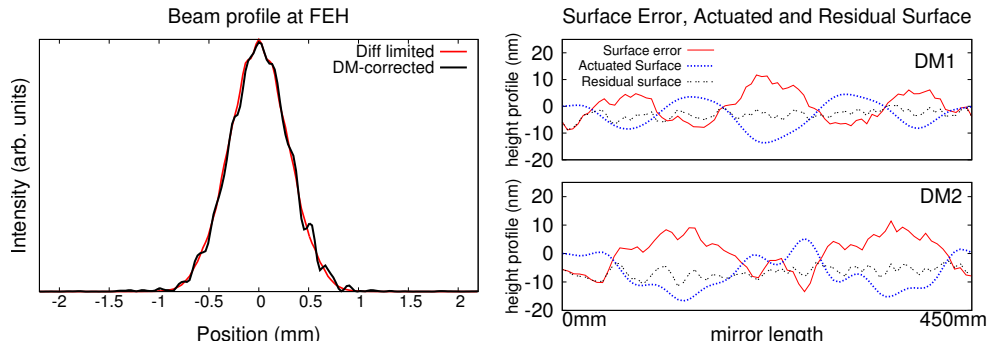
Figure 4. Left panel: beam profile at LCLS FEH hutch; diffraction limited and DM corrected profile are shown. right panel: Figure error, actuated surface and residual surface for the two DMs. Simulation was ran using a 1536x1536 size grid

In a different mirror deployment scheme, a single DM could be used to correct phase errors introduced by upstream or downstream optics. Complications related to the Talbot effect must then be considered. A sinusoidal signal introduced in the wavefront will cycle between phase and amplitude error as a function of propagation distance [8]. A single DM can only correct phase errors; therefore deployment location of the mirror is critical to achieve optimal wavefront correction. In fig 5 we report the results of a simulation where a single DM was deployed downstream of the second hard x-ray offset mirror at the LCLS beam transport system. The beam profile is plotted as a function of DM location, which was varied between 2.5m and 7.5 m from the second offset mirror. The optimal DM deployment location is found to be 5m downstream of the second offset mirror. This shows how our code will be very useful in determining optimal mirror deployment location once the beamline parameters are known.
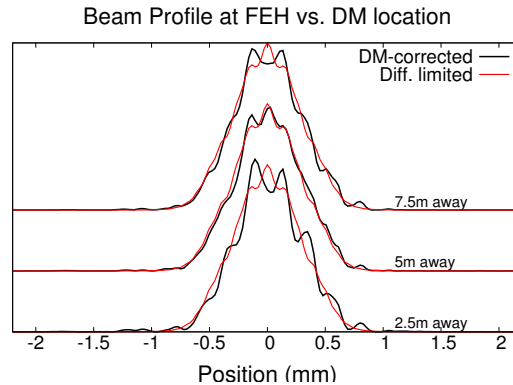
Figure 5. Diffraction limited and DM corrected beam profile at the FEH as a function of DM location with respect to the last LCLS offset mirrors. Dependence of wavefront correction efficiency on DM location is evident

3. Conclusions

LLNL, in collaboration with Northrop Grumman AOA Xinetics Inc., is currently developing a DM to be deployed at an x-ray light-source to achieve wavefront correction at x-ray wavelength. Deployment of the mirror at an x-ray facility is expected by the beginning of calendar year 2014. As part of the project we are also developing code based on wavefront propagation necessary to predict performance of our DM. In this manuscript we have shown how our custom-built code will provide useful insights on DM performance and optimal deployment location depending on the chosen x-ray beamline parameters.

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